ESTCP
Cost and Performance Report

(UX-0104)

Low-Order, Underwater Detonation

Novemeber 2002

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **NOV 2002**	2. REPORT TYPE	3. DATES COVERED **00-00-2002 to 00-00-2002**
4. TITLE AND SUBTITLE **Low-Order, Underwater Detonation**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Environmental Security Technology Certification Program (ESTCP),4800 Mark Center Drive, Suite 17D08,Alexandria,VA,22350-3605**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**29**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

1-D	One Dimensional
ATC	Aberdeen Test Center, Aberdeen, MD
BIP	Blow in Place
C4	a type of explosive
CFR	Code of Federal Regulations
Comp B	a type of explosive
DDESB	DoD Explosive Safety Board
DoD	Department of Defense
EIS	Environmental Impact Statement
EOD	Explosive Ordnance Disposal
ESTCP	Environmental Security Technology Certification Program
H-6	a type of explosive
HL-21	Nomenclature of a German-produced shaped charge
Imax	Maximum Impulse
mm	millimeter
Mk	Mark (a Military designation to identify equipment and ordnance)
NOSSA	Naval Ordnance Safety and Security Office
msec	milliseconds
NMFS	National Marine Fisheries Service
OSHA	Occupational Safety Health Administration
Pmax	Maximum peak pressure
RDX	Royal Demolition Explosive, a type of explosive
TNT	trinitrotoluene, a type of explosive
UXO	Unexploded Ordnance

ACKNOWLEDGMENTS

The author extends acknowledgment and his appreciation to Dr. Wardlaw of NSWC Indian Head, for his efforts on data reduction. The efforts of the Maritime Test Team at Aberdeen Test Center, particularly Joe Nokes and Mike McEvoy, were greatly appreciated, especially when testing extended into the evening hours.

1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

War activities, dumping, accidents, ordnance development, and military training have left significant quantities of unexploded ordnance (UXO) in coastal waters in the United States and abroad. UXO that is unsafe to move is countercharged or blown-in-place (BIP). The concern over underwater BIP is that it can cause acute environmental damage at a considerable distance from the detonation (Knowles, 1999). Damage to marine biota has to be balanced against the need for public safety.

Low-order detonation techniques have matured as a means to render safe surface UXO. Low-order detonation is characterized by the partial energetic reaction of high explosive filler in ordnance. There is very little data on generating low-order detonations with UXO underwater. The use of low-order detonation has potential to mitigate the acute blast effects by over 90 percent of that associated with conventional BIP procedures.

Tests on TNT-filled 155 mm projectiles and tritonal-filled Mk 82 bombs at the Aberdeen Test Center Briar Point Test Pond with a low-order tool were conducted in June and July 2001. The results showed that low-order detonation procedures were very effective in reducing the blast effects while causing a complete disruption of the ordnance. Pressure histories were equated to equivalent yields in pounds of TNT.

1.2 DEMONSTRATION OBJECTIVE

The objective of this demonstration was to develop a procedure and validate a low-order technique as an alternative to countercharging submerged UXO. The demonstration investigated the effectiveness and reliability of the (German) HL-21 shaped charge as a low-order detonation tool against *unfuzed* 155 mm High Explosive (HE) projectiles and MK 82 bombs. (Other test programs demonstrated that presence of fuzing does not affect low-order results). Effectiveness was measured by a reduction in the net explosive yield. The equivalent pounds of TNT needed to generate measured pressure and impulse determined the net explosive yield of a low-order detonation. (Additional data related to the growth and collapse of the detonation bubble was also gathered, as a result of comments received at the UXO Forum 2001 presentation of the Study in New Orleans). The test program was successfully completed.

1.3 REGULATORY DRIVERS AND OTHER ISSUES

While laws generally allow for the emergency destruction of UXO underwater in the interests of public safety, regulatory laws will affect UXO destruction methodology when the risk to public safety is not time-critical. The Marine Mammal Protection Act of 1972, as amended through 1997, the Endangered Species Act of 1973, and Executive Order 13089, Coral Reef Protection of June 11 1998, have bearing on techniques to sympathetically blow-in-place underwater UXO. In those instances where underwater UXO remediation may be attempted, an Environmental Impact Statement (EIS) may be required under the National Environmental Policy Act, Title 40, Code of Federal Regulations (CFR), Parts 1500-1508. In addition, Executive Order 13089 requires Federal activities whose actions could impact coral reefs to develop methods to mitigate potential damage.

Regulatory agency decision-makers may require statistical performance data before accepting underwater low-order detonation technology as a viable environmental mitigation technique.

1.4 DEMONSTRATION RESULTS

The data showed that the HL-21 could reduce explosive yields by 97-99 percent over conventional BIP procedures for Mk 82 bombs, and by 66-99 percent for 155 mm artillery rounds. For the Mk 82 bombs, 73 percent of trials resulted in low order events, while for the 155 rounds, 100 percent of trials resulted in low order events. The range of yield reductions results from multiple methods of calculation, and the consensus values favor the greater yield reductions. Secondary evidence of plume heights, fragmentation patterns, and residual unreacted explosives also verify low order results. Reliable reductions in explosive yield would afford both Navy EOD and civilian UXO companies greater windows of opportunity for ordnance disposal and minimize the potential risk to the marine environment and public safety.

1.5 STAKE HOLDER/END-USER ISSUES

Low-order detonation tools are not 100 percent effective, and the consequences of a high-order detonation must be anticipated. Low-order detonation tool performance varies with the procedure, type of ordnance, and the explosive fill. Two types of ordnance were used in these trials and this will limit the applicability of the test data. Additional controlled tests over a wider range of UXO, and monitoring of the technique in the field against dud-fired UXO may be required to gain confidence in the procedure.

Also, it is likely that bulk explosive and fuzing will remain after a low-order reaction in the field. The need to clean up this explosive waste stream will necessitate additional efforts over what is required for conventional BIP. The management of low-order waste may fall under the considerations of the Comprehensive Environmental Response, Compensation, and Liability Act, Resource Conservation and Recovery Act, Department of Defense Explosive Safety Board (DDESB), Department of Transportation, and State-specific regulations. Accordingly, low-order should be considered primarily when the environmental benefits of blast mitigation exceed the additional costs of cleanup. The issues of explosive chemical residue contamination resulting from low-order detonation were outside the scope of the current study.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

Low-order techniques are generally considered when the UXO cannot be moved to a safe-to-detonate area, and the collateral damage of a high-order detonation to the environment is of concern. Low-order detonation research is being conducted in order to develop a better understanding of the phenomenology, and there are still unresolved issues as to what occurs in a "low-order" reaction. In general, ordnance is designed to be insensitive and withstand mechanical and thermal insults, such as would occur from bullet or fragmentation impact. Thus, it is possible to penetrate some UXO with a high velocity projectile and not cause any reaction. Low-order detonation tools are designed to transmit enough reaction energy to the explosive charge so that the case ruptures as a result, but not so much energy as to cause a full detonative reaction. These tools typically use ounce quantities of explosives. The likelihood that the shock of an impinging shaped charge will detonate the explosives in UXO can be characterized by the parameter V2D, the velocity of the impinging jet squared times the diameter of the jet (Held, 1989). With insufficient shock to detonate, the explosive material may react with a rapid burn (deflagration) that may yet transition to detonation, depending on confinement, case material, charge size, and type of explosive. Thus, the consumption of explosive material in a low-order reaction will serve the purpose of reducing the explosive yield. The definition of "low-order" has accordingly been called "any explosive yield less than a full high-order." A 25 percent reduction in explosive yield was used to qualify low-order detonation tool performance (Gill, 1999). This arbitrary criterion was maintained as a definition of low-order. It is not unusual to reduce the explosive yield of UXO as determined by the peak pressure by more than 90 percent. Yield reductions based on impulse will be lower because of the slower time of reaction in low-order events.

TWD GmbH of Schrobenhausen, Germany, a subsidiary European Aeronautic Defence and Space Company (EADS), produces the EOD 21 ("Explosive Charge DM27, 18g, EOD SHAPED CHARGE") as a general purpose, low-order detonation "tool." The EOD 21, hereafter "HL-21," its common marketing name, contains 18 grams of explosive (~94 percent RDX). The HL-21 is 32 mm in diameter x 95 mm long, and has a specification of water tightness to a depth of 60 m. The tool also has brass decelerator plates available that can be mounted to the front of the shaped charge. Up to three plates may be added to slow the jet down for thin-cased ordnance. TDW advises using decelerator plates to keep the velocity of the jet below 2160 m/sec at the point of bulk explosive impact. The Army Research Lab characterized the HL-21 tool as performing as designed (Baker, 1997).

2.2 PROCESS DESCRIPTION

The HL-21 is positioned and aimed at the underwater UXO by a diver. This action invokes a host of rules and regulations regarding the transport, use, and storage of explosives, and the environmental impact assessment of underwater detonations.

- **Mobilization and Operational Requirements**

The Department of Defense Explosive Safety Board (see DoD directive 6055.9-STD "DoD Ammunition and Explosives Safety Standards," July 1999) will require an explosive safety

submission via the Naval Ordnance Safety and Security Activity (NOSSA) with the goal of ensuring that the operation is conducted safely. Federal regulations (29 CFR 1910.109 and 1926.912) govern safe practices for the storage of explosives and underwater blasting. Divers will require a portable magazine (ready service locker) to store HL-21s and other explosive material. Explosive-qualified divers will require detonation and support equipments including lines, augers, detonators, galvanometer, and blast machine.

Federal OSHA regulations (29 CFR 1910, Subpart T) mandate safe practices for commercial diving operations. U.S. Coast Guard regulations (46 CFR Ch. 1, 10-1-89 Edition, Subchapter V- Marine Occupational Safety and Health Standards) apply if the operation is off the continental coast. Each state has an administrative code that may impose additional regulations. The dive team will require diving equipment (suitable to the expected temperatures) and dive support equipment (boats and decompression chamber support).

The low-order operation may require environmental surveillance both before and after the low-order operation. Boats and/or aircraft may be necessary to ensure marine mammals are not in the area before the low-order shot is attempted. Divers may be required to search in the affected area and assess damage to fish and other biota after the shot.

- **Operational Procedure**

The HL-21 produces a shape charge jet that will travel through water, penetrate the case of the ordnance item, and initiate a low-order reaction. Low-energy blasting caps, non-electric blasting caps, or high-energy detonators (e.g. exploding bridgewire detonators) can be used to initiate the tool. Silicon RTV may be necessary to keep any water from getting in between the blasting cap and the HL-21.

Figure 1. HL-21 Set Up Against UXO.

Ordnance is attacked perpendicular to the surface, near the ogive, and away from any lug, ports or fuzing. The point of attack is not critical, but should be near the mid-section at an area of minimum case thickness. (The 155 mm projectile was attacked where the case thickness was nominally 14 mm. The Mk 82 was attacked where the case thickness was nominally 12.5 mm). See Figure 1 for pictures of typical test set-ups. Because the shots were prepared on the surface and lowered to a depth of 24 feet, extra care was taken to ensure that the set-up did not shift.

- The HL-21 was held by a plastic stand attached to a bent, fabricated flat bar. The flat bar was securely held by band clamps around the ordnance. Duct seal (a soft, pliable material) and plastic tie wraps were used to secure the HL-21 to the plastic stand. (Metal band clamps or dense materials should not be in contact with the outside of the HL-21 in order to preclude any possible disruption to jet formation).

Total Molding Concepts of Winchester, VA, (540) 665-8408, produced the plastic stand that was used in the trials. The stand that comes with the HL-21 would probably suffice in a field environment. Some consideration to the set up would be required with either stand for soft muds or strong currents.

The standoff distance between the face of the HL-21 and the surface of the ordnance is a critical parameter in using the HL-21 to attack UXO. The standoff distance will determine the velocity of the shaped charge jet when it impacts the bulk explosive load of UXO. The standoff distance used for all 155 mm projectile shots was 60 mm with an estimated precision of +/- 1 mm. Several standoff distances were tried for the Mk 82 bombs, varying from 30 to 60 mm, again with an estimated precision of +/- 1 mm. The 33 mm standoff was used with success, although a high-order detonation did occur with this standoff. A dowel rod cut to the desired length was used to set the stand off distance for each shot, seen in Figure 1. The dowel rod was removed before the shot. (A more desirable alternative would be to use a spacer that could be left in place and not affect the jet). The manufacturer recommends that two or more HL-21s be used on larger ordnance, but this configuration was not tested.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

Low-order testing was performed for EOD tool development during Phase II Developmental Test (DT-II) series for the Main Charge Disrupter (MCD) (Gill, 1999). The test program established the MCD and HL-21 as effective tools for causing low-order reactions in surface ordnance. (The HL-21 was not selected because operators did not want a pre-packaged tool). The MCD tool is not configured for underwater usage. The effectiveness of the MCD varied with the type of ordnance and the explosive fill; however, the *presence or absence of fuzing* had no affect on performance. Also, there was no appreciable difference in MCD effectiveness on whether test ordnance was from a *magazine or dud-fired*.

Preliminary tests with the HL-21 were conducted in January 2001 at the Army Research Laboratory's Blossom Point Test Facility in Charles County, MD. The purpose of testing was to establish low-order feasibility and procedures prior to the full-scale instrumented underwater tests scheduled in June/July 2001. Because the HL-21 tool is normally fired in air, it was expected that water would disturb and decelerate the jet. Initial tests against steel witness plates established that adequate penetration was achieved with a 60 mm standoff (distance from the front of the tool to the surface of the plate) and a 90-degree angle of attack. Tests were then conducted against 155 mm projectiles using partially buried 55-gallon drums filled with water, Figure 2. All five tests

Figure 2. Blossom Point Trials.

against 155 mm projectiles (TNT-filled, no fuzing) with at least 60 degree angles of attack resulted in successful low-order detonations. (One test at a 45-degree angle of attack resulted in no penetration of the ordnance). Although there was no instrumentation to quantify the yield reduction in these trials, the differences between an intentional high-order detonation and the HL-21-induced low-order detonations on the test fixtures were significant. In one test, the drum was just split open. The low-order detonations of the 155 mm generated large-sized fragmentation, with normal edge fracture (at 90 degrees). Unreacted TNT was also present after some shots. In an intentional high order detonation, the drum was destroyed, the relatively small 155 mm fragmentation had sharp fracture edges at 45 degrees, and no bulk explosive could be found. Explosive limits (on the quantity of explosive that could be detonated) at the Blossom Point Test Facility did not permit the testing of HL-21s against Mk 82 Bombs.

2.4 STRENGTHS, ADVANTAGES, AND WEAKNESSES

The primary advantage of low-order detonation over BIP stems from the mitigation of acute blast effects. A secondary advantage is that it may be economical to low-order UXO in place instead of moving it to a separate disposal site. The logistical expense of moving underwater UXO would depend on the local conditions, the size and nature of the UXO, and the distances involved. The disadvantage to low-order detonation is that it will create a waste stream from the unreacted bulk explosive.

3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The test goal was to measure the reliability and effectiveness of an HL-21 attack on unfuzed ordnance. (As noted earlier, trials with surface ordnance have indicated that the presence or absence of fuzing does not affect low-order detonation tool performance). Reliability in terms of this study refers to the ability of the HL-21 to function properly underwater. A reliability failure would occur if the HL-21 was fired and there was no penetration through the ordnance or witness plate. Effectiveness refers to two measures, both related to the explosive event resulting from the HL-21 attack on UXO. One objective is to determine the statistical likelihood of a low-order detonation, given that the HL-21 functioned properly. The second objective is to determine the equivalent explosive weight in pounds-TNT, given that a low-order detonation took place. Related to this measure is the relationship of the explosive yield reduction for low-order detonations over what would have occurred in "normal" BIP procedures. (In this latter case, a 1.4 lb. donor charge will be assumed for a 155 mm projectile BIP procedure, and a 5 lb. donor charge will be assumed for a Mk 82 bomb). Explosive yield equivalencies provide an analytical basis to compare performance and average results. Explosive yields were estimated from ATC-gathered pressure histories. NSWC Indian Head interpreted the data for TNT yield equivalency based on pressure, impulse, and bubble characteristics. General performance metrics used to evaluate the low-order detonation tool are presented below in Table 1.

Table 1. Performance Metrics.

Type of Performance Objective	Primary Performance Criteria	Expected Performance
Quantitative	Reliability (ability to penetrate UXO). Effectiveness (statistical likelihood of a low-order detonation) Effectiveness (percent reduction in yield over BIP procedures)	Pressure history of each event correlated to equivalent explosive yield through peak pressure, impulse, and bubble period modeling.
Qualitative	Reliability	Test observation (plume height, fragmentation evidence).
	Ease of Use	Observation

3.2 TEST SITE SELECTION

The major factors in site selection were environmental compliance, cost, and an ability to accommodate two hundred-pound-plus underwater explosive shots. The Briar Point UNDEX pond at Aberdeen Test Center (ATC), Aberdeen, MD, has the infrastructure to accommodate complex instrumentation. ATC is a Department of Defense Major Range and Test Facility base (MRTFB).

3.3 TEST FACILITY CHARACTERISTICS

The Briar Point UNDEX test pond (Figure 3) is a man-made facility built primarily for Navy tests that involve the detonation of explosives on the surface or underwater. The pond has a surface diameter of 330 feet, a maximum depth of 60 feet, a flat- surface bottom diameter of 70 feet, and side slopes of 2.5 to 1. The perimeter of the pond is armored with stone to prevent erosion from wave action. The volume of the pond is approximately 84,000 cubic yards of water (17 million gallons). The surrounding soil is comprised mostly of silty clay.

Figure 3. Briar Point Pond.

The maximum charge weight that can be detonated in the UNDEX pond is the equivalent of 400 pounds of TNT. Because the pond is physically and environmentally isolated from the local water sources, it can support a wide range of tests without inflicting harm to the environment.

3.4 PHYSICAL SET-UP AND INSTRUMENTATION

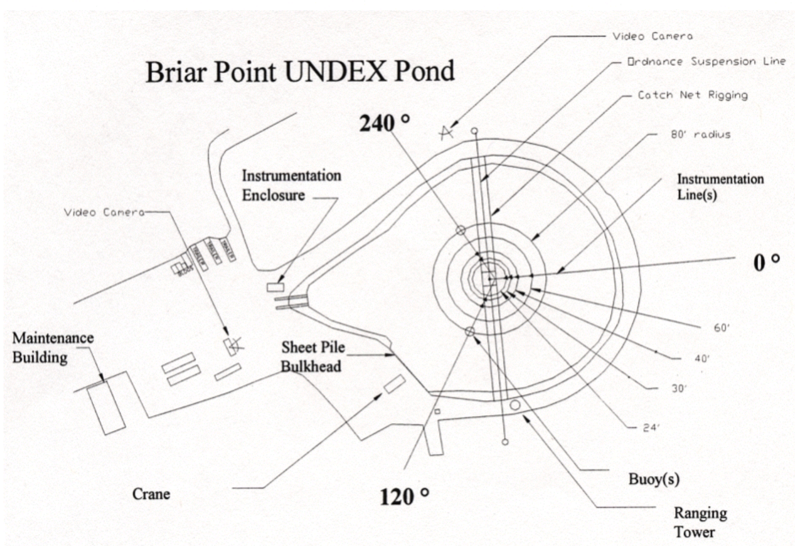

Figure 4. Test Instrumentation Layout.

An array of gauges at a depth of 24 feet was used along three radii to capture the pressure history of the 155 mm projectile and Mk 82 bomb low-order reactions (Figure 4). The gauges were placed further away during the Mk 82 trials to better protect them from inadvertent high order detonations. The depth of one sensor set was increased to 29 feet in order to avoid interference from a cable bundle. An additional set of sensors was placed 100 feet away to capture the bubble pulse and bubble period of the low-order detonations. PCB microsensors and Endevco gauges (models 8511 and 8530) were used. (NSWC Carderock participated in two 155 mm shots with their independent tourmaline sensors along the zero degree radii). The instrumentation lines/cables were supported by ½-inch diameter cable suspended over the Pond. Support buoys were used to reduce cable tension. The Ballistic Test Site Terminal (BTST) was placed under a trailer shield to protect it. Standard one thousand-foot lengths of instrumentation cable were used to run to all of the gauge locations. ATC instrumentation personnel fabricated gauge supports or stinger assemblies to hang

from the instrumentation support lines. Additionally, the sixty-foot high tower on site was marked every 20 feet to provide a plume height reference.

Three real time video cameras were used. One camera was placed on the opposite side of the pond so that the tower markings or graduations and the shot plumes were visible within the field of view. A second camera was positioned to have an unobstructed view to the center of the pond where the ordnance will be suspended. The third camera was positioned inside the BTST to provide monitoring of the digitizer for signs of potential pre-triggering. No high-speed cameras were used.

3.5 DATA SAMPLING

- A breakscreen was taped to the ordnance to provide a time zero reference. Pressure-time recordings were taken with a BTST, set for 100 kHz frequency response, and sampling at 800,000 samples per second. A record of 100,000 samples provided a time history of 125 milliseconds in duration for each pressure gage. This permitted recording of the pressure-time history of the initial shock wave. Data from some gauges had to be discarded. The history of the pressure wave was used to calculate equivalent explosive yields for each shot.

- Case fragmentation and explosive residue from each shot was collected in a 20 by 20 foot cargo net suspended ~40 feet deep, 16 feet underneath the test shot. The fragmentation was photographed. The bulk explosive was weighed; the weight of explosive still attached to ordnance case pieces was estimated. The presence of explosive residue, large fragmentation, and fragmentation fractures at 90 degrees were used to qualitatively assess whether a low-detonation occurred.

- An estimate of the plume height was made from the video footage for each shot.

3.6 ANALYTICAL PROCEDURES

The purpose of data analysis is to determine whether a low- or high-order event took place. Physical evidence was gathered as discussed in data sampling for a qualitative assessment. Equivalent explosive yield calculations were used to provide a quantitative measure of the output of a low-order reaction. The procedures used to compute the equivalent explosive yield were adapted from methods intended to apply to underwater high-order detonation phenomena. This is analogous to methods used to characterize surface low-order detonation effectiveness. However, additional information is available with the bubble created by an underwater explosion, such as "bubble period", a measure of the time for the detonation bubble to grow and collapse to a minimum diameter.

Peak pressure and impulse are parameters associated with explosive shock that are derived or estimated from the recorded pressure history of an underwater explosion. The equivalent amount of TNT that could duplicate these parameters in a high-order detonation can be estimated by empirical calculation known as Similitude (Price, 1979) or by analytical methods such as 1-D Euler (Wardlaw, 1998). The 1-D Euler method can also be used to estimate equivalent explosive weight from the bubble phenomena derived from the recorded pressure history. Low-order detonations lack the rapid rise and exponential decay of pressure that is characteristic of high-order detonations. Consequently, the different pressure history parameters will provide different estimates for the

equivalent yield. For example, the (relatively) slow rise and fall of pressure in a low-order detonation results in higher computed yields for impulse than expected for the peak pressure associated with the impulse trace.

The planned procedure to compute yields for each of the three radii with instrumentation was abandoned in favor of computing the yield based on all gauges at a given range. Dr. Wardlaw, NSWC Indian Head, took the following approach to compute equivalent yield.

Part I. Construct a table of:

a) Maximum experimental shock pressure
b) Maximum experimental shock impulse
c) Maximum experimental bubble pressure
d) Maximum experimental bubble impulse
e) Bubble period

   1). Remove data from obviously bad channels;
   2). All pressure and impulse traces were compared at each standoff, without regard to direction; the median, not average or maximum values were used.

Part II. Compute an equivalent weight of TNT for each test based on similitude:

a) Maximum shock pressure
b) Maximum shock impulse

   1). Construct by 1-D Euler computation tables of maximum pressure and impulse for the shock phase.
   2). Construct by 1-D Euler computation tables of maximum pressure and impulse for the bubble phase.

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

The HL-21 was used 48 times in the course of the study and functioned properly 47 times for a reliability of ~94 percent at the 80 percent confidence level. In one test, the HL-21 jet broke apart and failed to penetrate a Mk 82 bomb.

4.1.1 155 mm Projectile Results

The HL-21 was able to induce a low-order detonative reaction in 155-mm projectiles 21 times in 21 attempts using a 60-mm standoff and angle of attack at least 60 degrees. This procedure was 92 percent reliable at the 80 percent confidence level. Figure 5 shows a typical 155-mm projectile low-order detonation, with complete disruption of the round. The fragments could be assembled into the complete round.

Figure 5. Typical 155 mm Low-Order Test Result.

Explosive yield calculations varied with the pressure history parameter and analytical methodology. All analytical methods showed that low-order detonation effectively reduces the energy released into the environment over conventional BIP (with a 1.4 pound TNT-equivalent charge). Table 2 summarizes the reduction in yield for each calculation methodology relative to BIP for 16-instrumented low-order detonations.

Table 2. 155 mm Results (Pounds TNT Equivalent).

	Shock				Bubble		Bubble Period
	Pmax		Imax		Pmax	Imax	
	1D Euler	Similitude	1D Euler	Similitude	1D Euler	1D Euler	1D Euler
Avg (# TNT)	0.338	0.114	2.077	5.341	0.192	1.049	2.342
Std Dev	0.057	0.048	0.722	2.003	0.025	0.209	0.629
% of 14.6#	2.3%	0.8%	14.2%	36.6%	1.3%	7.2%	0.16
% of 16# (BIP)	2.1%	0.7%	13.0%	33.4%	1.2%	6.6%	14.6%
Reduction (over BIP)	97.9%	99.3%	87.0%	66.6%	98.8%	93.4%	85.4%

The three times difference in average yield (0.34 lbs. of TNT vs. 0.11 lbs. of TNT) calculated by 1-D Euler and Similitude using peak pressure (Pmax) has to be considered in context that the yield reductions for both methods exceed 97 percent over what would have been expected for BIP (16 pounds). Impulse (Imax) calculations showed higher yields over those calculated for Pmax, and the differences between the two analytical methodologies are reversed (2.1 pounds vs. 5.3 pounds TNT equivalent). Bubble period calculations provide intermediate estimates of yield over those calculations based on peak pressure and impulse. All estimates exceed the 25 percent reduction in yield that was used to arbitrarily define "low-order."

Divers gathered fragmentation and TNT residue after each instrumented test. The presence of unreacted TNT and large fragmentation after a test provided physical evidence of a low-order detonation. Two intentional high-order detonations yielded no TNT and the fragmentation had sharp edges. The recovered explosive from each low-order detonation was weighed and the weight of TNT bound to fragmentation was estimated. On average, about 25 percent of the original explosive fill was recovered after a low-order detonation. The possibility of residue from one test being recovered on a following test could not be ruled out. There was no way to determine how much explosive residue was not caught in the cargo net. It took approximately twenty minutes for divers to recover the residue and fragmentation from the 20 x 20-foot cargo net suspended 16 feet below the test shot. Divers spent an average of 32 minutes recovering the fragmentation from two intentional high-order detonations.

The plume heights of successful low-order events (typically less than 6 feet) were visibly different from the intentional high-order detonations of the 155-mm projectiles (23 and 42 feet high), and are additional physical evidence of low-order detonations. The plume heights of the low-order detonations corresponded somewhat to the yield calculations.

4.1.2 Mk 82 Bomb Results

The HL-21 was able to induce a consistent low-order reaction in the tritonal-filled Mk 82 bombs after several adjustments in the standoff. All bombs were x-rayed prior to the trials, but no correlation of the test results with the x-rays was apparent. Initial tests using a 60-mm standoff resulted in (4) "no-reaction" test results in the first (9) shots. The no-reactions were characterized by a small hole (~0.1 inch diameter) in the bomb, which otherwise remained intact. Clearly the HL-21 did not impart enough energy into the explosive to initiate the low-order reaction. An HL-21 standoff of 30 mm resulted of a high-order detonation, the first in the test program. The gap was widened to 33 mm and this provided the most consistent low-order response, minimizing the risk of no reaction and high-order detonation.

Figure 6. Typical Mk 82 Bomb Low-Order Test Result.

The 33- or 35-mm standoffs resulted in 8 low-order reactions in 11 trials, discounting one test when the tool malfunctioned. One unintentional high-order detonation and two no reactions occurred with a 33-mm standoff. Figure 6 shows the results of Mk 82 low-order test, with near complete disruption of the bomb.

Explosive yield calculations for Mk 82 bombs varied with the analytical methodology, but the TNT-equivalent yields were so small relative to the main charge (192-lb tritonal, equivalent to 243-lb TNT) as to make the differences inconsequential. Average yield calculations (lbs TNT equivalency) for the 13 low-order detonations in Table 3 showed that low-order detonation significantly reduces the energy released into the environment over conventional BIP (assuming a 5-lb TNT-equivalent donor charge).

Table 3. Mk 82 Low-Order Yield Results (Pounds TNT Equivalency).

	Shock				Bubble		Bubble Period
	Pmax		Imax		Pmax	Imax	
	1D Euler	Similitude	1D Euler	Similitude	1D Euler	1D Euler	1D Euler
Avg (# TNT)	0.450	0.190	2.751	7.120	0.405	1.667	4.779
Std Dev	0.450	0.301	2.200	6.004	0.064	1.319	3.051
% of 243#	0.2%	0.1%	1.1%	2.9%	0.2%	0.7%	2.0%
% of 248# (BIP)	0.2%	0.1%	1.1%	2.9%	0.2%	0.7%	2.0%
Reduction (over BIP)	99.8%	99.9%	98.9%	97.1%	99.8%	99.3%	98.0%

As with the 155-mm projectile testing, Imax calculations using Similitude showed the least reduction in explosive yield. Again the yields calculated with 1-D Euler and Similitude reverse relative magnitude with the Pmax and Imax parameters. Bubble period calculations provide an intermediate estimate of yield between peak pressure and impulse calculations. The yield equivalencies for the two unintentional high-order detonations were not calculated.

On average, divers recovered over 130 pounds (>70 percent) of the 192 pounds of explosive fill after each low-order. They took an average of 25 minutes to recover fragmentation and residue from low-order events, and an average of 42 minutes to recover the fragmentation from the two high-order detonations. The presence of unreacted explosive provided physical evidence of a low-order reaction. In some tests, significant quantities (tens of pounds) of tritonal remained bound in the nose portion of the bomb.

The plume heights of low-order detonations were visibly different form the inadvertent high-order detonations of the Mk 82 bomb. The plume heights for low-order detonations do not correspond well to the respective calculations for explosive yield. For example, one test had the highest computed yield for the low-order successes, yet it did not have the highest plume.

4.2 DATA ASSESSMENT

4.2.1 Data Analysis

The 5 parameters (maximum pressure, maximum impulse, bubble pressure, bubble impulse and bubble period) used to determine yield varied with the parameter selected and the analytical method. Because low-order detonation phenomena have just recently come under scrutiny, there is no referee to determine which methodology is the more correct representation of yield. The physical evidence of low-order (recovered explosive residue, large fragmentation, and low plume heights) correlated well to reduced yields vs. evidence of high-order events (no explosive residue, small fragmentation, and high plume heights).

It is not surprising that the "yield reduction" numbers vary with the selected parameter. Analysis of the experimental data and generation of the equivalent weight is complicated by the differences between the low- and high-order pressure histories. Figure 7 depicts the pressure-time trace of a low-order detonation and an intentionally induced high-order detonation.

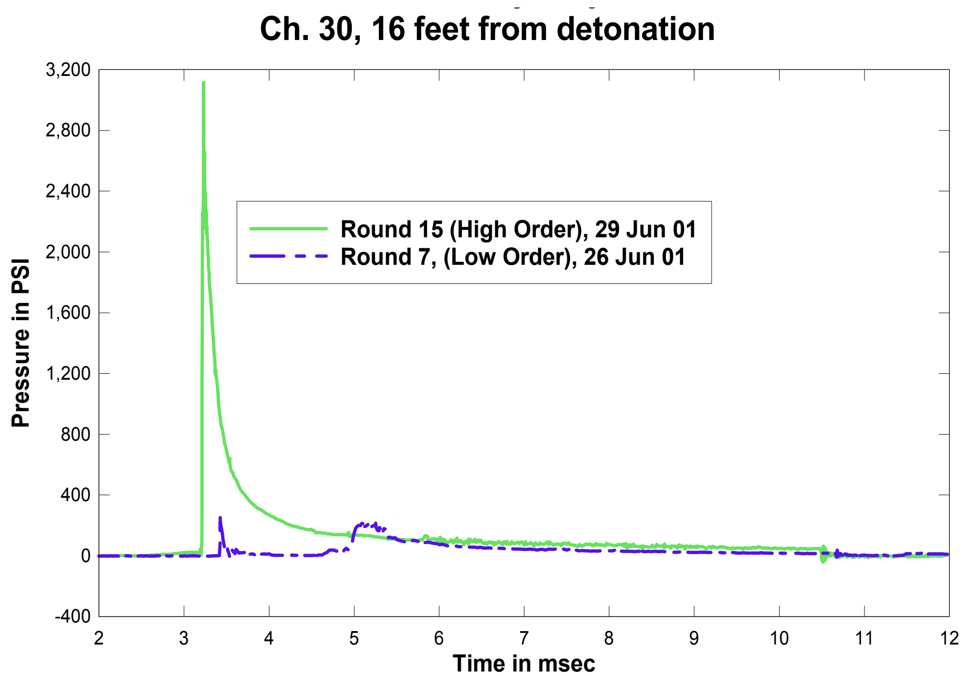

Figure 7. Pressure Histories of 155 mm Projectile High- and Low-Order Detonations.

The pressure pulse from the HL-21 (the first small peak with a rapid rise time, Round 7) is followed ~2 milliseconds later by the low-order detonation of the 155 mm. The low-order detonation is characterized by a gradual build up of pressure and slow decay, compared to the high-order detonation with its near instantaneous build up of pressure (at 3 milliseconds) and rapid exponential decay. A consequence of this difference is that the equivalent weight of TNT with respect to peak pressure differs from that computed with respect to maximum momentum. The TNT equivalent weight based on pressure is much lower than that based on impulse. The two analytical methods (1-D Euler and Similitude) show greater disagreement for impulse calculations (pounds of TNT) than they do for peak pressure calculations (ounces of TNT). The Euler solution is not encumbered by an assumed pressure distribution, and the maximum impulse occurs when the pressure decays to the ambient level. The reliability of Similitude impulse figures is questionable, since the Similitude impulse is based on an approximate pressure history curve. Also, the energy released during low-order events appears to fluctuate from one test to another. The combination of these factors produced variation in the equivalent TNT estimates.

Regardless of the parameter or analytical methodology, quantitative analysis showed significant reductions in the explosive energy released into the environment as a consequence of low-order reactions. It should also be noted that the difference in low-order yield impulse calculations between the 155-mm projectile and Mk 82 bomb was not large, only ~30 percent, in spite of a factor of 15 difference in their respective bulk TNT-equivalent weights. This result shows that low-order detonation yields are not directly proportional to the quantity of explosive present. Accordingly, low-order detonation yields reductions for ordnance larger than Mk 82 bombs may also be relatively high. Note that this relationship is only suggested for TNT-based explosive fills.

4.3 TECHNOLOGY COMPARISON

Civilian EOD technicians would naturally prefer to use BIP over low-order, as it does not create an additional waste stream and there is no question about the safety of the technique. The analysis of pressure histories in this study has demonstrated that the use of low-order detonation technology offers a methodology to mitigate the acute underwater blast effects otherwise associated with conventional Blow-in-Place procedures. Biological response to the pressure and impulse generated by a low-order detonation has not been investigated. Biological damage to marine life has been reported as being proportional to the peak pressure and/or impulse generated by a high-order underwater explosion (Young, 1991). The calculations for safe standoff distances from underwater explosions use "TNT equivalency" and are based on an estimate of 90 percent chance of survivability. Empirical scaling laws take the form:

$$R = k\ w^a$$

Where: R is the safe standoff distance in feet
k is a scaling factor dependent upon the species (e.g., k = 560 for turtles, 578 for dolphin calves)
w is the net explosive weight (n.e.w.) in pounds (TNT equivalent)
a is an exponential decay factor (e.g., a = 0.333 for turtles, 0.28 for dolphin calves)

Thus, for a 155 mm projectile with 14.6 pounds TNT and the use of a 1.4 pound donor BIP charge, the safe standoff for sea turtles would be estimated at ~1400 feet. The safe standoff distance using a low-order detonation tool would be ~300 feet, if it succeeded in reducing the explosive yield of BIP (projectile plus donor explosive) by 99 percent and *if the biological response to low-order detonations can be reliably expressed in TNT equivalency*. The smaller radius would mean an approximate 95 percent reduction in the volume of water affected by the blast. The reduced volume of affected water would result in a smaller "take" of turtles that might otherwise go unobserved within the danger zone. Post-blast surveillance by divers (generally required) for affected biota would be easier to accomplish within the reduced volume of affected water.

It cannot be determined within the scope of this study whether low-order detonation yield calculations would either under- or over-estimate the damage radius as represented by these empirical equations. However, the unique pressure history data of low-order detonations is now available, should specific damage mechanisms ever be determined.

This page left blank intentionally.

5.0 COST ASSESSMENT

5.1 COST REPORTING

The low-order study was conducted at a Government-controlled test sites specially constructed and permitted for demolition/explosive studies. The study did not incur the costs elements that would normally be associated with the remediation of underwater UXO by a commercial diving organization. NAVEODTECHDIV received $117K to manage the study, procure test tools, and report the results. Aberdeen Test Center received $178K to conduct and instrument the tests. Naval Surface Warfare Center (NSWC), Indian Head was funded $15K to provide data analysis support. NSWC Carderock was funded $10K to provide instrumentation support. Accordingly, many of the sub category cost elements could not be tracked per se, so estimates are provided.

Table 4. Cost Reporting.

Cost Category	Sub Category	Costs ($K)
Fixed Costs		
Capital Costs	Planning	35
	Blossom Point Procedure Tests	15
	Briar Point Pond Set Up/Demobilization	50
	X-Ray of Ordnance	13
	NSWC Carderock Instrumentation	10
Variable Costs		
Operation and Maintenance Costs	Labor, travel, miscellaneous	162
	NSWC Data Analysis Support	15
Other Technology Specific Costs		
	Disposal of Explosive Residue	20
	Total Costs	**320**

5.2 COST ANALYSIS

The major cost elements for remediation of underwater UXO evolve primarily around planning, diver operations, explosive operations, and environmental and safety surveillance. The costs to low-order or BIP underwater UXO are primarily driven by those factors that affect and support diving operations. The principle cost differences between low-order and BIP are the need to recover and dispose of any explosive residues after a low-order detonation. These elements include:

Planning

An approved Explosive Safety Submission that describes how demolition and explosive materials will be handled and controlled needs to be approved by the Naval Ordnance Safety and Security Activity and the Department of Defense Explosive Safety Board. Other regulatory environmental compliance issues, impact statements, etc. may also have to be addressed.

Dive Operations

Federal OSHA regulations (29 CFR 1910, Subpart T) mandate safe practices for commercial diving companies. Each state has an administrative code that may impose additional regulations. Commercial EOD diving companies typically base their operating procedures on the US Navy Dive manual. Consequently, a minimal dive team is composed of four divers. The dive team will require diving equipment and dive support equipment (boat charter and decompression chamber support). Federal regulations, 29CFR Part 5, Subpart A - Davis Bacon and Related Acts and Procedures, govern the labor costs of divers. Cost per diver in wages and fringe benefits is $72/hour; G&A and overhead would ~double the cost to $144/hour. Labor rates will increase 25 percent for depths greater than 50 fsw and increase another 25 percent for depths greater than 100 fsw. Water currents and temperatures will place limits on dive operations and will be cost drivers by limiting productivity. Divers will require a dive boat with crew of sufficient size to carry all their equipment and to shelter them from the environment. If the expected depth/duration of a dive is expected to require decompression, then a decompression chamber must be provided on-site (if not otherwise accessible) with qualified personnel, at an estimated cost of $1200/day (Global Divers, LA).

The cost to conduct one day of dive operations (4 divers) over an 8-hour day is estimated as follows:

Dive suit/scuba rental	$600
Air for scuba	50
Labor	4,600
Boat Charter	500
Decompression Chamber	1,200
Total	$6,750/day

Explosive Operations

The difference between the cost of an HL-21 (~$100) and 5 lbs. of pentolite booster explosive (~$20) is relatively insignificant compared to the labor and overhead costs of conducting diver explosive operations. Federal regulations (29 CFR 1910.109 and 1926.912) govern safe practices for the storage of explosives and underwater blasting. Divers will require a portable magazine (ready service locker) to store HL-21s and other explosive material, estimated at a capital expense of $5000. Divers will require detonation and support equipments including lines, augers, detonators, galvanometer, and blast machine, estimated at a capital expense of $2000. These two later capital expenses can be amortized assuming a 10 year economic life, 5 percent interest at $906/year. Assuming four explosive operations a year would bring the expense to ~$200/operation. Once UXO has been low-ordered, the explosive waste must be stored at a permitted range, packaged/classified, and certified safe for transport (by a military official) to a permitted site. R and R Trucking (Joplin, MO) transportation costs for explosive wastes are estimated at $1.47/mile for loads less than 1000 pounds. Safety Kleen (Colfax, LA) has a minimum treatment fee of $1600, otherwise charging $3.85 to $4.67/pound for treatment of class 1.1D explosive wastes.

Environmental/Safety Surveillance and Issues

Explosive operations may require a Medivac helicopter on standby, at an estimated expense of $1000/hour. Explosive operations may require range safety boat(s) to keep pleasure craft away from the operating area, at $400/day. Helicopter surveillance may be necessary to ensure endangered species are clear of the area (e.g., gray whales, green sea turtles, etc.) The rental cost for a Hughes 500 helicopter is estimated at $650/flying hour.

The following table summarizes the major costs of low-order and BIP. It is based on the disposal of four Mk 82 bombs in one day in an area where Medivac standby is unnecessary, but that a range boat and a surveillance helicopter (4 hours) are required. It assumes that the low-order technique is reliable. It further assumes 130 pounds of explosive are generated from each low-order shot and must be transported to a treatment facility 500 miles away.

Table 5. Cost Comparison of Low-Order and BIP.

Cost Category	Low-Order Detonation ($)	BIP ($)
Planning/Management	5,000	5,000
Dive Operations	6,750	6,750
Demolition Equipment	200	200
Demolition Material	400	80
On-site Surveillance	3,000	3,000
Disposal of Explosive Residue	2,350	0
Total	17,685	15,030
Cost per Mk 82 Bomb	4,400	3,750

Cost benefit analyses should consider the reduced acute environmental damage incurred with low-order detonation.

This page left blank intentionally.

6.0 REFERENCES

1. Baker, P. and R. Summers, 1997, "Characterization of the HL-42 and HL-21 Dud-Disposer Shaped Charges as EOD Devices," U.S. Army Research Laboratory Technical Report, ARL-TR-1362, June 1997.

2. Gill, D., 1999, "Development Testing (DT:IIA): Container, Main Charge Disrupter (MCD)," NAVEODTECHDIV Technical Note TN-468, July, 1999.

3. Held, M., 1989, "Initiation Phenomena With Shaped Charged Jets," Ninth Symposium (International) on Detonation, OCNR-113291-7, Volume 2, 1989.

4. Knowles, D., 2000, National Marine Fisheries Service Endangered Species Act Section 7 Consultation Biological Opinion re: "Underwater Explosions for Ordnance Disposal for the Fort Kamehameha Sewage Outfall Project (F-PI-00-1: MMD)," 7 July 2000.

5. Pedersen, A., 1996, "Challenges of UXO in the Marine Environment," UXO Forum 1996.

6. Price, R., "Similitude Equations for Explosives Fired Underwater", NSWC TR 80-299, Nov. 1979.

7. Wardlaw, A., "1-D Godunov Hydrocode Suite", IHTR 2088, Sept. 1998.

8. Young, G., 1991, "Concise Methods for Predicting the Effects of Underwater Explosions on Marine Life," NAVSWC MP-91-220, 1 July 1991.

This page left blank intentionally.

APPENDIX A

POINTS OF CONTACT

Andy Pedersen
Project Manager
Naval Explosive Ordnance Disposal
Technology Division
Telephone: (301) 744-6850, x250
Fax: (301) 744-6947
Email: pedersen@eodpoe2.navsea.navy.mil

Drew Wardlaw
Data Analyst
Naval Surface Warfare Center,
Indian Head Division
Telephone: (301) 744-6850, x250
Fax: (301) 744-6947
Email: WardlawAB@ih.navy.mil

Joe Nokes
Test Manager
U.S. Army Aberdeen Test Center
Telephone: (410) 278-6945, x250
Fax: (410) 278-6944
Email: jnokes@atc.army.mil

ESTCP Program Office

901 North Stuart Street
Suite 303
Arlington, Virginia 22203

(703) 696-2117 (Phone)
(703) 696-2114 (Fax)

e-mail: estcp@estcp.org
www.estcp.org